

OPTICAL PROPERTIES OF HOST GALAXIES OF EXTRAGALACTIC NUCLEAR WATER MASERS

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ABSTRACT

We study the optical properties of the host galaxies of nuclear 22 GHz ($\lambda = 1.35$ cm) water masers. To do so, we cross-match the galaxy sample surveyed for water maser emission (123 detections and 3806 non-detections) with the SDSS low-redshift galaxy sample ($z < 0.05$). Out of 1636 galaxies with SDSS photometry, we identify 48 detections; out of the 1063 galaxies that also have SDSS spectroscopy, we identify 33 detections. We find that maser detection rate is higher at higher optical luminosity (M_B), larger velocity dispersion (σ), and higher [O III] $\lambda 5007$ luminosity, with [O III] $\lambda 5007$ being the dominant factor. These detection rates are essentially the result of the correlations of isotropic maser luminosity with all three of these variables. These correlations are natural if maser strength increases with central black hole mass and the level of AGN activity. We also find that the detection rate is higher in galaxies with higher extinction. Based on these results, we propose that maser surveys seeking to efficiently find masers should rank AGN targets by extinction-corrected [O III] $\lambda 5007$ flux when available. This prioritization would improve maser detection efficiency, from an overall $\sim 3\%$ without pre-selection to $\sim 16\%$ for the strongest intrinsic [O III] $\lambda 5007$ emitters, by a factor of ~ 5 .

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — radio lines: galaxies — masers

1. INTRODUCTION

Water maser emission at 22 GHz ($\lambda = 1.35$ cm) is currently the only tracer of warm dense molecular gas in the inner parsec of active galaxy nuclei (AGNs) and has been detected to date in more than 100 AGNs (e.g., Braatz et al. 1996; Henkel et al. 2005; Kondratko et al. 2006b; Braatz & Gugliucci 2008; Greenhill et al. 2008). Some of these masers are associated with rotating, highly inclined disk structures close to the central engines (“disk masers”) and have been used for a broad variety of astrophysical studies, including the mass estimation of supermassive black holes, the mapping of accretion disks, and the determination of geometric distances (e.g., Miyoshi et al. 1995; Greenhill et al. 1997; Greenhill & Gwinn 1997; Ishihara et al. 2001; Greenhill et al. 2003; Braatz et al. 2010; Kuo et al. 2010).

Nuclear water masers have been claimed to be associated with Seyfert 2 or low-ionization nuclear emission-line region (LINER) systems (e.g., Braatz et al. 1997; Kondratko et al. 2006b). It is also plausible that AGNs which host masers are more likely associated with high X-ray obscuring columns (N_H) than those without maser detections (e.g., Braatz et al. 1997; Madejski et al. 2006; Zhang et al. 2006; Greenhill et al. 2008; Zhang et al. 2010). There also appear to be correlations of isotropic maser luminosity with the X-ray luminosity (Kondratko et al. 2006b) and the far-infrared (FIR) luminosity (Henkel et al. 2005) of the host AGNs, though the underlying mechanisms are not clear. As additional words of caution in interpreting these correlations, the in-

ferred X-ray luminosities are subject to large uncertainties owing to high columns, and the true (i.e., beamed) maser luminosities are unknown in most cases.

The overall detection rate of nuclear water masers is only $\sim 3\%$. Even if AGNs with higher X-ray luminosity and/or higher obscuring column more likely host masers, there is no existing large sample of AGNs with X-ray data available for target selection. However, if masers are preferentially found in galaxies with certain optical properties, we can improve maser detection efficiency by selecting galaxies with these properties as targets from existing large galaxy surveys, such as the Sloan Digital Sky Survey (SDSS; York et al. 2000), the 2dF Galaxy Redshift Survey (2dFGRS; Colless et al. 2001), and the 6dF Galaxy Survey (6dFGS; Jones et al. 2004).

The goal of this work is to systematically investigate the optical properties of maser host galaxies. We cross-match the SDSS low-redshift galaxy catalog with the complete galaxy sample surveyed for maser emission. We find that maser detection rate is higher at higher optical luminosity, larger velocity dispersion, higher [O III] $\lambda 5007$ luminosity, and higher extinction. We present these results in Section 2. In Section 3, we suggest that a plausible explanation of these results is that maser strength is correlated with the central black hole mass and the AGN activity of the host galaxies. In Section 4, we suggest that maser surveys rank AGN targets by extinction-corrected [O III] $\lambda 5007$ flux, which should greatly improve the detection efficiency. We adopt a Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s⁻¹ Mpc⁻¹.

2. DETECTION EFFICIENCY

2.1. Data

2.1.1. The complete galaxy sample surveyed for maser emission

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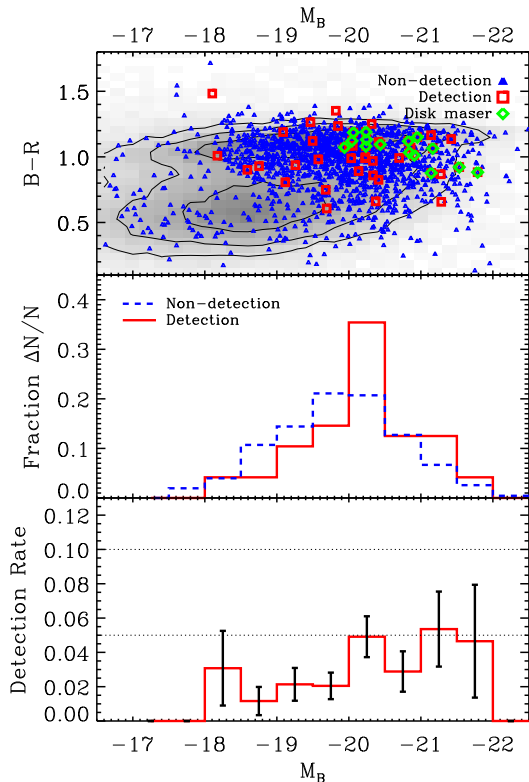


FIG. 1.— *Top panel:* Color-magnitude diagram. For comparison, we show the distribution of the whole low- z photometric sample as the gray scale. The contours enclose 40%, 80%, and 90% of the sample. Blue triangles represent non-detections and red squares indicate maser detections. We also show the disk masers with green diamonds but we cannot draw robust conclusions because of the small sample size. *Middle panel:* Distribution of M_B . We show the ratio of the number of galaxies per 0.5 mag to the size of each sample. *Bottom panel:* Detection rate as a function of M_B . To guide the eye, we show two horizontal dotted lines at 5% and 10%. The error bars represent Poisson errors. The detection rate appears to be higher at higher luminosity.

To construct a complete sample of galaxies surveyed to date for maser emission, we combine the catalogs (as of December 1, 2010) maintained on the website of the Megamaser Cosmology Project (MCP⁴) and that of the Hubble Constant Maser Experiment (HoME⁵). For maser detections, we use the MCP catalog that is complete. We however exclude those masers known to be associated with star-forming regions (IC 10, M 33, IC 342, M 82, NGC 253, NGC 3359, NGC 3556, NGC 2146, He 2-10, NGC 4038/39, NGC 4214, NGC 5253), as noted in the either HoME or MCP catalogs. Although it is not labeled in either catalog, we also exclude NGC 4194, since it is an ongoing merger and has strong star formation in the center (e.g., Balzano 1983) and the detected maser may not be associated with its nucleus. There are 123 detections in total and we list them in Table 1. Among these, at least 41 are probably associated with disk structures, as noted in the HoME catalog. The evidence is either from direct mapping of the emission distributions using Very Long Baseline Interferometry (VLBI)

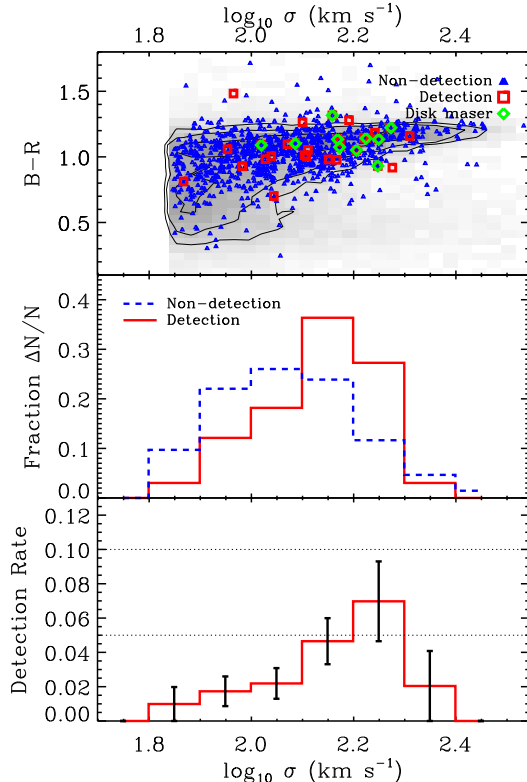


FIG. 2.— Similar to Figure 1, but with velocity dispersion (σ). Note σ lower than 70 km s^{-1} is not reliable due to the instrumental resolution of the SDSS spectrograph; we do not consider galaxies below that limit. The detection rate is higher at larger σ .

or inferred from spectroscopy (e.g., Madejski et al. 2006; Greenhill et al. 2008). For galaxies without successful maser detections (non-detections), we combine both catalogs from HoME and MCP to build the whole sample. After removing duplicates between the catalogs, we have 3806 non-detections in total. The overall detection rate is therefore about 3%.

We note that this complete sample consists of galaxies surveyed using different telescopes with different detection sensitivities. The highest sensitivity comes from the Green Bank Telescope (GBT) survey (e.g., Braatz et al. 2004). The 1σ rms sensitivity of the GBT survey is $\sim 3 \text{ mJy per } 24.4 \text{ kHz } (\sim 0.33 \text{ km s}^{-1})$ channel (Braatz et al. 2004). Assuming a characteristic maser linewidth of 10 km s^{-1} , this corresponds to a 3σ maser flux limit of 0.1 Jy km s^{-1} .

2.1.2. The SDSS low- z galaxy sample

To systematically study maser detection efficiency, we require a complete parent sample. The SDSS survey has provided such a sample of galaxies with uniform imaging and spectroscopy. For spectral properties, we use the measurements by the MPA-JHU group⁶ (e.g., Tremonti et al. 2004). We use the latest version that corresponds to SDSS Data Release 7 (DR7, Abazajian et al. 2009). We choose to look at velocity dispersion (σ , in km s^{-1}) and [O III] $\lambda 5007$ luminosity ($L_{[\text{O III}] \lambda 5007}$, in

⁴ <https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject>

⁵ <https://www.cfa.harvard.edu/~lincoln/demo/HoME/index.html>

⁶ <http://www.mpa-garching.mpg.de/SDSS/DR7/>

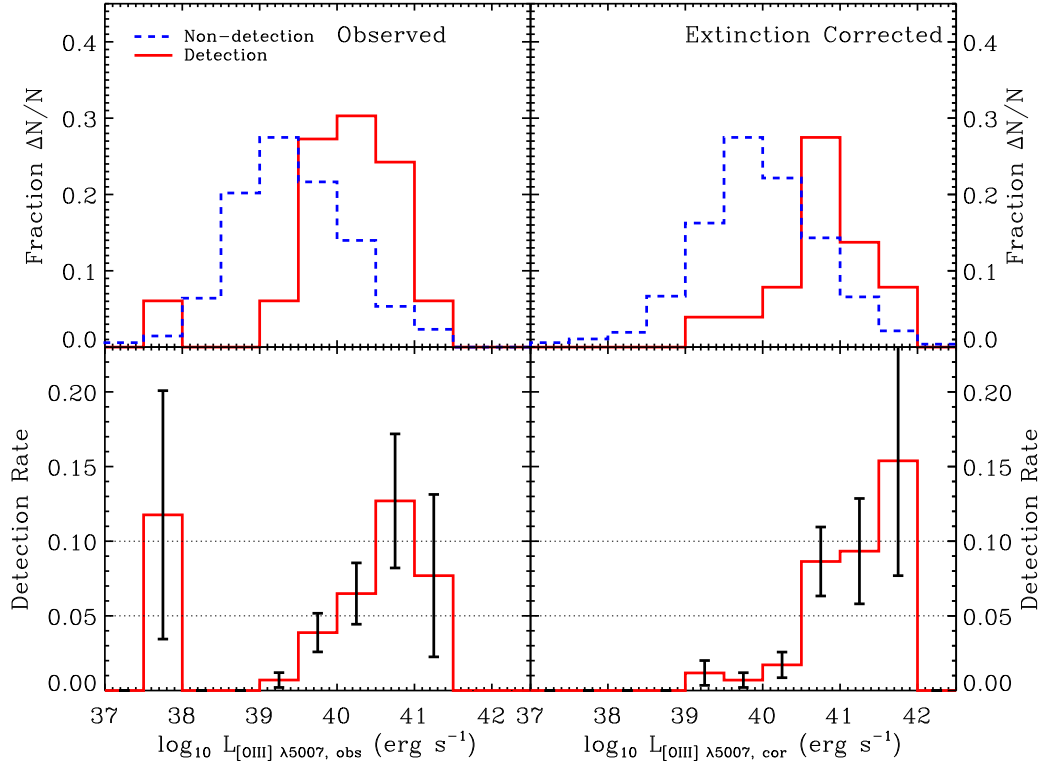


FIG. 3.— The left panels are similar to the lower two panels in Figure 1 and 2, but with observed [O III] $\lambda 5007$ luminosity ($L_{[\text{OIII}]\lambda 5007, \text{obs}}$). In the right panels, we correct the extinction to obtain the intrinsic [O III] $\lambda 5007$ luminosity ($L_{[\text{OIII}]\lambda 5007, \text{cor}}$) using $L_{[\text{OIII}]\lambda 5007, \text{cor}} = L_{[\text{OIII}]\lambda 5007, \text{obs}} / ((H\alpha/H\beta)/(H\alpha/H\beta)_0)^{2.94}$, where $H\alpha/H\beta$ is the observed Balmer decrement and we assume the intrinsic Balmer decrement $(H\alpha/H\beta)_0 = 3$. The detection rate is higher at higher [O III] $\lambda 5007$ luminosity. The effect is stronger for $L_{[\text{OIII}]\lambda 5007, \text{cor}}$, implying that detections on average have higher extinction than non-detections.

erg s^{-1}), since velocity dispersion is closely related to central black hole mass (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000) and [O III] $\lambda 5007$ luminosity is well-correlated with AGN activity (e.g., Heckman et al. 2005). It is well-known that [O III] $\lambda 5007$ can be severely obscured by material in the host galaxy (e.g., Diamond-Stanic et al. 2009). We therefore calculate the intrinsic [O III] $\lambda 5007$ luminosity ($L_{[\text{OIII}]\lambda 5007, \text{cor}}$) by correcting the observed $L_{[\text{OIII}]\lambda 5007, \text{obs}}$ using the following formula (e.g., Bassani et al. 1999): $L_{[\text{OIII}]\lambda 5007, \text{cor}} = L_{[\text{OIII}]\lambda 5007, \text{obs}} / ((H\alpha/H\beta)/(H\alpha/H\beta)_0)^{2.94}$, where $H\alpha/H\beta$ is the observed Balmer decrement and we assume the intrinsic Balmer decrement $(H\alpha/H\beta)_0 = 3$. Because of the instrumental dispersion of the SDSS spectrograph, velocity dispersion measurements smaller than 70 km s^{-1} are not reliable⁷; we thus only consider galaxies with $\sigma > 70 \text{ km s}^{-1}$. Finally, since only four (4C +05.19, SDSS J0804+3607, Mrk 34, and 3C 403) out of the 123 maser detections are farther than $z = 0.05$ and all of them are not in the MPA-JHU catalog, we limit the sample to low-redshift galaxies with $z < 0.05$. At the faint end, the flux limit of the SDSS spectroscopic survey is $r = 17.77$, which corresponds to $M_B \sim -18$ at $z = 0.05$.

Due to the difficulty of automatic photometric processing of big galaxies, the SDSS catalog is missing many

nearby, bright galaxies, even though they are contained within the SDSS imaging footprint. For photometry, we therefore use the low- z catalog ($z < 0.05$) from the NYU Value Added Galaxy Catalog (NYU-VAGC⁸; Blanton et al. 2005). This low- z photometric catalog includes any low-redshift galaxies from the Third Reference Catalog of Bright Galaxies (RC3; de Vaucouleurs et al. 1991; Corwin et al. 1994) for which we have *ugriz* imaging from SDSS, but which are not in the SDSS catalog. We use the latest version of this catalog that corresponds to SDSS Data Release 6 (DR6, Adelman-McCarthy et al. 2006). We have compared the photometry of those galaxies in the SDSS catalog with that from DR7 and found they are very consistent, therefore using DR6 for photometry should not introduce any bias. We derive absolute magnitudes using the *kcorrect* package (v4.1.4; Blanton & Roweis 2007). For easier comparison with previous studies, we choose the B band magnitude M_B to indicate optical luminosity. Note here the magnitude is the total magnitude for the whole galaxy.

We cross-match maser detections and non-detections with the SDSS low- z sample, and identify 48 detections (15 disk masers) and 1588 non-detections with SDSS photometry, among which, 33 detections (10 disk masers) and 1030 non-detections have reliable spectral measure-

⁷ <http://www.sdss.org/dr7/algorithms/veldisp.html>

⁸ <http://sdss.physics.nyu.edu/vagc/>

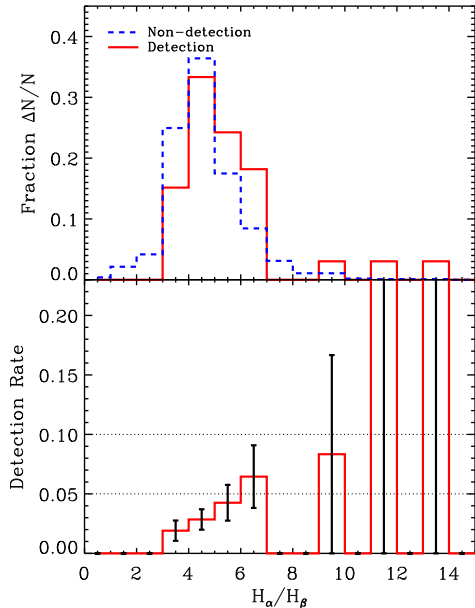


FIG. 4.— Similar to the lower two panels in Figure 1 and 2, but with Balmer decrement $H\alpha/H\beta$. The detection rate is higher at higher $H\alpha/H\beta$.

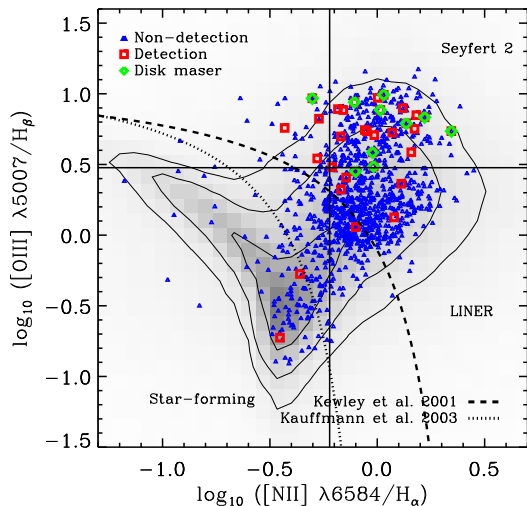


FIG. 5.— Emission line diagnostic diagram (Baldwin et al. 1981, BPT). For comparison, we show the distribution of the whole low- z spectroscopic sample as the gray scale. The contours enclose 40%, 80%, and 90% of the sample. The dotted and dashed lines are the demarcation lines separating AGN and star-forming galaxies defined by Kauffmann et al. (2003) and Kewley et al. (2001). The solid vertical and horizontal lines at $[N II] \lambda 6584/H\alpha = 0.6$ and $[O III] \lambda 5007/H\beta = 3.0$ are the conventional separating lines for Seyfert 2 galaxies (above) and LINERs (below). There are 25 (8) detections above (below) the horizontal line, compared to 296 (734) non-detections.

ments, i.e., with $\sigma > 70 \text{ km s}^{-1}$. We note that the overall detection rate in this sample is $\sim 3\%$, the same as in the total sample, so using this sample should not introduce a bias in the analysis presented below. We present measurements for detections in Table 1. In the next subsection, we study the dependence of maser detection efficiency on optical luminosity and spectral properties using these samples.

2.2. Results

2.2.1. All galaxies surveyed for water masers

Figure 1, 2, and 3 present maser detection efficiency as a function of M_B , σ (in log scale), $L_{[O III] \lambda 5007, \text{obs}}$ (in log scale), and $L_{[O III] \lambda 5007, \text{cor}}$ (in log scale). In the top panels of Figure 1 and 2, we show the detections (blue triangle) and non-detections (red square) in the color-magnitude/ σ diagram. For comparison, we also show the distribution of the whole SDSS low- z sample in gray scales and contours. Masers are concentrated in systems with larger $B-R$ and total luminosity, but there are very few blue, low luminosity (presumably disk-dominated) galaxies that have been surveyed for emission. We also show the disk masers with green diamonds, but we cannot draw robust conclusions because of the small sample size. In the middle panels of Figure 1 and 2 and in the top panels of Figure 3, we show the distribution of detections and non-detections. Performing Kolmogorov-Smirnov test yields P-values 0.01, 0.02, 2×10^{-8} , and 3×10^{-9} , respectively, indicating a low probability that they are drawn from the same distribution, particularly for $L_{[O III] \lambda 5007}$. The bottom panels present the detection rate, which is apparently higher at brighter M_B , larger σ , and higher $L_{[O III] \lambda 5007}$. The dependence of the detection efficiency on σ appears stronger than that on M_B , while the dependence on $L_{[O III] \lambda 5007}$ is more striking than that on both M_B and σ .

Figure 3 also shows that maser detection efficiency depends more strongly on $L_{[O III] \lambda 5007, \text{cor}}$ than on $L_{[O III] \lambda 5007, \text{obs}}$, implying that detections could on average have higher extinction than non-detections. Previous studies show that AGNs which host masers are more likely associated with high X-ray obscuring columns than those without maser detections (e.g., Greenhill et al. 2008; Zhang et al. 2010). We therefore investigate the detection efficiency as a function of the observed Balmer decrement in Figure 4. In the top panel, a Kolmogorov-Smirnov test yields a P-value 0.009, indicating that detections and non-detections are likely drawn from different distributions. The lower panel shows the detection rate is indeed higher at higher extinction.

In Figure 5, we show the emission line diagnostic diagram (Baldwin et al. 1981, BPT). We show two widely-used demarcation criteria that separate AGNs (to the right) and star-forming galaxies (to the left), by Kewley et al. (2001, the dashed line) and by Kauffmann et al. (2003, the dotted line). The vertical solid line at $[N II] \lambda 6584/H\alpha = 0.6$ and the horizontal solid line at $[O III] \lambda 5007/H\beta = 3.0$ are the conventional demarcation lines for Seyfert 2 (above) and LINER-like (below) galaxies (e.g., Veilleux & Osterbrock 1987). It is apparent that most surveys have mainly targeted AGNs.

Among AGNs, masers are clearly more often detected in Seyfert 2 galaxies rather than LINERs. For exam-

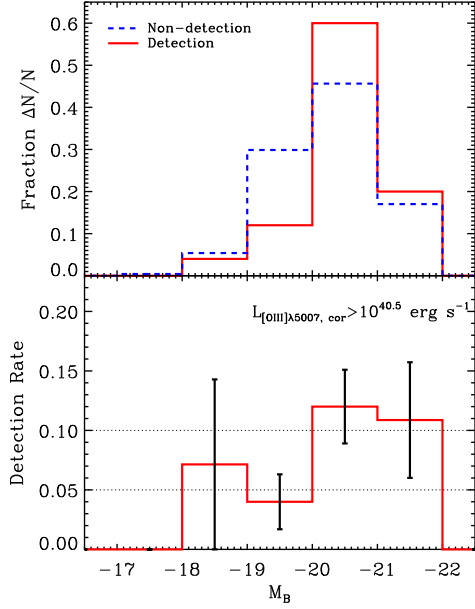


FIG. 6.— The same as the lower two panels in Figure 1, but for galaxies with $L_{[\text{OIII}]\lambda 5007, \text{cor}} > 10^{40.5} \text{ erg s}^{-1}$ only. Note we double the bin size because of a smaller sample size. Among the 33 detections, 25 have $L_{[\text{OIII}]\lambda 5007, \text{cor}} > 10^{40.5} \text{ erg s}^{-1}$; and among 1030 non-detections, 242 have $L_{[\text{OIII}]\lambda 5007, \text{cor}} > 10^{40.5} \text{ erg s}^{-1}$. The overall detection rate ($\sim 9\%$) is higher than that ($\sim 3\%$) without pre-selection in Figure 1. The detection rate is also higher at higher luminosity.

ple, in Figure 5, there are 25 maser detections associated with Seyfert 2 galaxies (out of 321 in total, above the horizontal line), but only eight associated with LINERs (out of 742 in total, below the horizontal line). It is yet unknown what fraction of LINERs are AGNs (e.g., Ho et al. 2003; Sarzi et al. 2010) and we are not sure about the underlying mechanisms responsible for the preferred association of masers with Seyfert 2 galaxies over LINERs. However, if LINERs are low-luminosity counterparts of Seyfert 2 galaxies, as some studies claim (e.g., Ho et al. 2003), then the low maser detection efficiency among LINERs could be simply a reflection of the $L_{[\text{OIII}]\lambda 5007}$ dependence we found in Figure 3, since the majority of LINERs without maser detections ($\sim 90\%$) have $L_{[\text{OIII}]\lambda 5007, \text{cor}} < 10^{40.5} \text{ erg s}^{-1}$. After all, LINERs are known to have low $[\text{O III}] \lambda 5007$ luminosities relative to Seyfert 2 galaxies (e.g., Heckman et al. 2004).

2.2.2. Galaxies with $L_{[\text{OIII}]\lambda 5007, \text{cor}} > 10^{40.5} \text{ erg s}^{-1}$ only

We have shown that maser detection rate depends more strongly on $L_{[\text{OIII}]\lambda 5007}$ than on M_B and σ , as in Figures 1, 2, and 3. However, these three quantities are themselves correlated in the galaxy population. We here investigate further whether there is a residual dependence of detection efficiency on M_B and σ even for galaxies with strong $[\text{O III}] \lambda 5007$ emission.

Among the 33 detections, only eight have $L_{[\text{OIII}]\lambda 5007, \text{cor}} < 10^{40.5} \text{ erg s}^{-1}$. Meanwhile, 789 out of 1030 non-detections have $L_{[\text{OIII}]\lambda 5007, \text{cor}} < 10^{40.5} \text{ erg s}^{-1}$. We therefore pre-select galaxies with $L_{[\text{OIII}]\lambda 5007, \text{cor}} > 10^{40.5} \text{ erg s}^{-1}$ (25/33 detections and

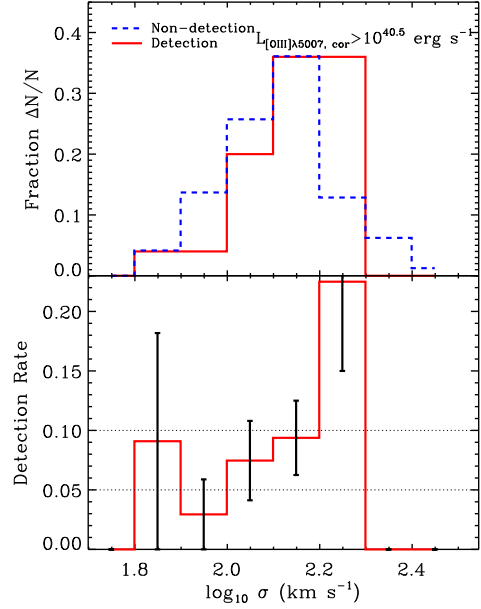


FIG. 7.— The same as the lower two panels in Figure 2, but for galaxies with $L_{[\text{OIII}]\lambda 5007, \text{cor}} > 10^{40.5} \text{ erg s}^{-1}$ only. The overall detection rate is higher than without pre-selection in Figure 2. The detection rate is higher at larger σ .

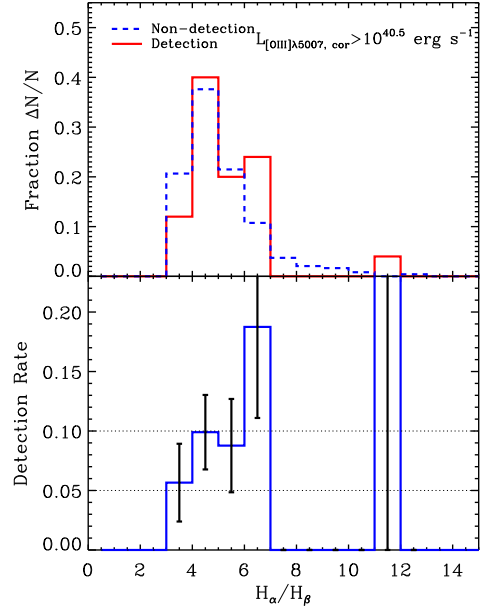


FIG. 8.— The same as the lower two panels in Figure 4, but for galaxies with $L_{[\text{OIII}]\lambda 5007, \text{cor}} > 10^{40.5} \text{ erg s}^{-1}$ only. The overall detection rate is higher than without pre-selection in Figure 4. The detection rate is higher at higher $\text{H}\alpha/\text{H}\beta$.

242/1030 non-detections) and show the detection rate as a function of M_B and σ for this pre-selected sample in Figure 6 and 7. We also show the detection rate as a function of Balmer decrement $H\alpha/H\beta$ in Figure 8. Compared to the results for the whole sample (Figure 1, 2, and 4), there are still detections over the whole range of M_B , σ , and $H\alpha/H\beta$, and the detection rate is still higher at brighter M_B , larger σ , and higher $H\alpha/H\beta$. The overall detection rate, however, is $\sim 9\%$ compared to $\sim 3\%$ without pre-selection. We therefore conclude that among M_B , σ , $[O III] \lambda 5007$, and $H\alpha/H\beta$, $[O III] \lambda 5007$ is the dominant factor when determining maser detection efficiency.

3. DISCUSSION

3.1. Isotropic luminosity of masers

Above, we found that water maser detection rate increases with $[O III] \lambda 5007$ luminosity ($L_{[O III] \lambda 5007}$), velocity dispersion (σ), and optical luminosity (M_B). We speculate that these correlations may be a consequence of an underlying correlation of these parameters with water maser luminosity. The true luminosity of masers is difficult to measure because the maser emission is likely to be beamed (e.g., Elitzur 1992) and estimates of the beaming angle require a detailed model of the maser, which can only be inferred in the cases with well-understood geometries from VLBI observations (e.g., Miyoshi et al. 1995). In place of true luminosity, we adopt apparent luminosity, which is based on the premise of “isotropic” emission of radiation. The isotropic luminosity can be computed readily from the flux densities observed in spectra. On the other hand, the flux density can be variable on time scales of months (e.g., Bragg et al. 2000; Braatz et al. 2003; Herrnstein et al. 2005; Castangia et al. 2008), which introduces another uncertainty. Nonetheless, analysis using the stand-in of isotropic luminosity provides an opportunity to investigate whether the speculated correlations exist. From the literature, we have collected isotropic luminosities for 66 masers.

Maser surveys are flux-limited and the lower maser detection rate in galaxies with lower $L_{[O III] \lambda 5007, \text{obs}}$, smaller σ , and fainter M_B could be because most masers in these galaxies are too faint to be detected. We investigate the flux limit in Figure 9, where we plot isotropic luminosities as a function of redshift. Although these detections are from a variety of surveys that have different sensitivities, they appear to be consistent with 0.1 Jy km s^{-1} as the effective limit. This limit is consistent with a plausible detection threshold of 10 mJy (3σ) in a 1 km s^{-1} channel and blends of Doppler components on the order of 10 km s^{-1} , as seen in the spectra (e.g., with GBT, Braatz et al. 2004).

To investigate the correlations between maser luminosity and optical properties of the host galaxies, we complement the sample with M_B , σ , $L_{[O III] \lambda 5007, \text{obs}}$, and $H\alpha/H\beta$ (thus $L_{[O III] \lambda 5007, \text{cor}}$) from the literature. In addition to those with SDSS photometry or spectroscopy, we have compiled $L_{[O III] \lambda 5007, \text{cor}}$ ($H\alpha/H\beta$), $L_{[O III] \lambda 5007, \text{obs}}$, σ , and M_B for 36, 40, 43, and 54 masers with measured isotropic luminosities. We present these data in Table 1. The combined sample is inhomogeneous in terms of selection, technique, and instrument parameters, and this (in ad-

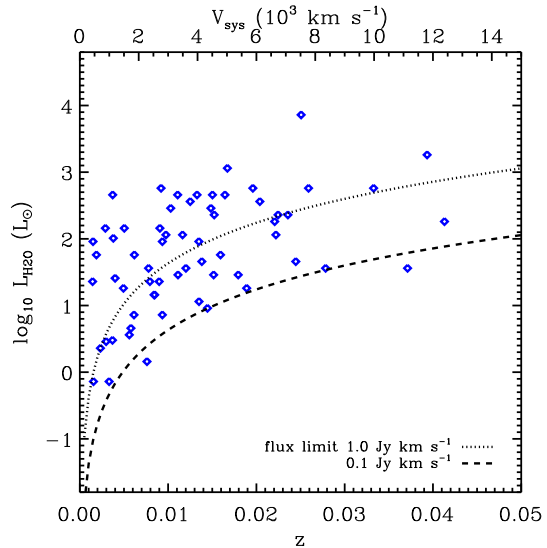


FIG. 9.— Isotropic maser luminosity as a function of redshift for 66 extragalactic nuclear masers. The dotted line shows the flux limit 1.0 Jy km s^{-1} , and the dashed line shows the flux limit 0.1 Jy km s^{-1} .

dition to the use of isotropic luminosity as a stand-in – noted earlier) may be expected to increase the scatter in any correlations.

In Figure 10, we plot $\log_{10} L_{[O III] \lambda 5007, \text{cor}}$, $\log_{10} L_{[O III] \lambda 5007, \text{obs}}$, $\log_{10} \sigma$, and M_B against the isotropic luminosity $\log_{10} L_{H_2O}$. Although the scatter in all relations is relatively large, the variables are clearly correlated. Assuming a uniform error of 0.5 dex for $\log_{10} L_{H_2O}$, we perform least-squares fits with the following linear relations: $\log_{10} L_{H_2O} = a + b(x - x_0)$, where we choose x_0 to be the medians, 41.39 (dex), 40.43 (dex), 2.16 (dex), and -20.58 (mag) for $x = \log_{10} L_{[O III] \lambda 5007, \text{cor}}$, $\log_{10} L_{[O III] \lambda 5007, \text{obs}}$, $\log_{10} \sigma$, and M_B , respectively, to minimize the correlation between a and b . We show the results with the dashed lines. The intercepts and slopes (a , b) for $\log_{10} L_{[O III] \lambda 5007, \text{cor}}$, $\log_{10} L_{[O III] \lambda 5007, \text{obs}}$, $\log_{10} \sigma$, and M_B are $(1.65 \pm 0.13, 0.31 \pm 0.10)$, $(1.66 \pm 0.12, 0.22 \pm 0.11)$, $(1.64 \pm 0.11, 2.67 \pm 0.64)$, and $(1.75 \pm 0.11, -0.21 \pm 0.13)$, respectively. We can draw a robust conclusion that masers are stronger in hosts with higher $[O III] \lambda 5007$ luminosity, larger σ , and higher optical luminosity, as implied from the detection efficiency results.

We would like to emphasize that the best-fit slopes and intercepts here should be taken with caution. First, as mentioned above, the isotropic luminosity is a poor indicator of maser strength and the sample of optical properties is not homogeneous. Second, stronger masers are more easily detected, and at the faint end there should be a detection bias favoring stronger masers scattered above the real correlations; the real slopes therefore should be steeper than the best-fit ones. Finally, the sample size is small and a few outliers could significantly affect the fitting. However, the conclusion is robust that maser strength increases with $[O III] \lambda 5007$ luminosity, σ , and optical luminosity.

In Figure 4, we showed that maser detection rate is

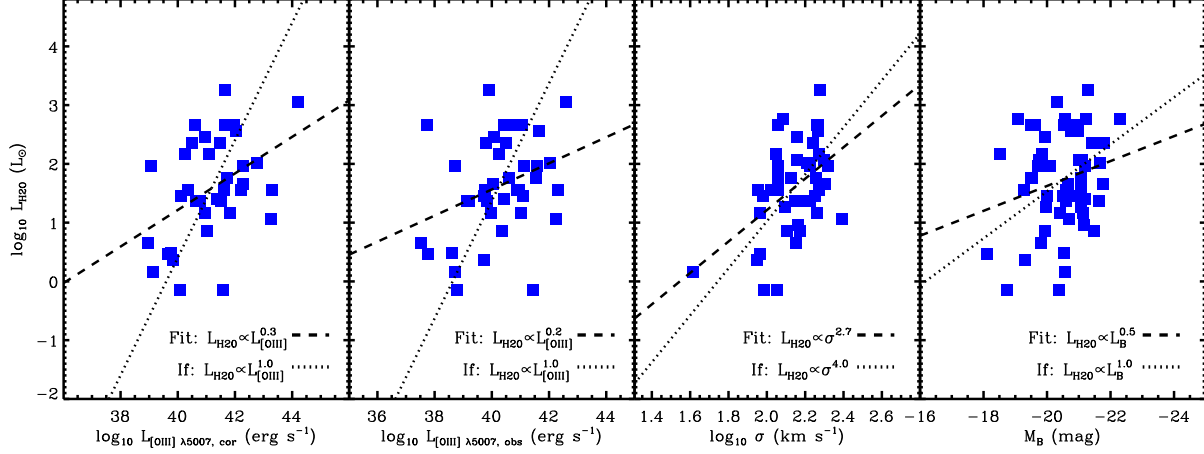


FIG. 10.— Relations between isotropic maser luminosity ($L_{\text{H}_2\text{O}}$) and $L_{[\text{OIII}]\lambda 5007, \text{cor}}$, $L_{[\text{OIII}]\lambda 5007, \text{obs}}$, σ , and M_B of the host galaxies. The dashed lines are the linear least-squares fits assuming a uniform error of 0.5 dex in $\log_{10} L_{\text{H}_2\text{O}}$. The dotted lines show the linear least-squares fits with the slopes fixed assuming that $L_{\text{H}_2\text{O}} \propto L_{\text{AGN}} \propto M_{\text{BH}}$, and $M_{\text{BH}} \propto L_B \propto \sigma^4$, and $L_{\text{AGN}} \propto L_{[\text{OIII}]\lambda 5007}$.

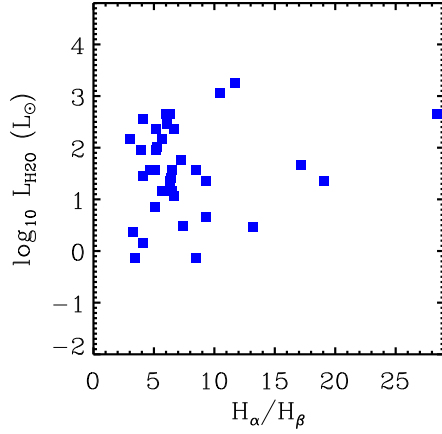


FIG. 11.— Relation between isotropic maser luminosity ($L_{\text{H}_2\text{O}}$) and H_α/H_β of the host galaxies.

higher at higher H_α/H_β . As for the other parameters, this could result from an underlying relation between maser luminosity and extinction. We investigate such a relation in Figure 11. A linear least-squares fit gives $(a, b) = (1.54 \pm 0.15, 0.03 \pm 0.03)$ for $x_0 = 6.31$. We do not find a convincing relation (with only $\sim 1\sigma$) between maser luminosity and Balmer decrement, indicating that there might not be a direct linear relation between $\log_{10} L_{\text{H}_2\text{O}}$ and Balmer decrement. We discuss this result more in Section 3.3.

3.2. Correlations of maser emission with central black hole mass and AGN activity?

It has long been proposed that water maser emission is closely related with the central black hole. Assuming that a thin viscous accretion disk is obliquely illuminated by a central X-ray source, Neufeld & Maloney (1995) find that the critical outer radius R_{cr} at which the disk becomes atomic and the maser emission ceases

follows $R_{\text{cr}} \propto L_{2-10}^{-0.43} \dot{m}^{0.81} M_{\text{BH}}^{0.62}$, where L_{2-10} is the 2 – 10 keV X-ray luminosity of the host galaxy, \dot{m} is the mass accretion rate, and M_{BH} is the central black hole mass. If we assume that the X-ray luminosity is proportional to AGN bolometric luminosity (L_{AGN}), and that L_{AGN} is proportional to the accretion rate (e.g., Frank, King, & Raine 2002), we consequently reach $R_{\text{cr}} \propto L_{\text{AGN}}^{0.38} M_{\text{BH}}^{0.62}$. Considering that in the geometrical maser models (e.g. Miyoshi et al. 1995), maser spots do not cover the whole nuclear disk but rather lie on several radial arms, we assume that total maser luminosity $L_{\text{H}_2\text{O}} \propto R_{\text{cr}}$ (but see Kondratko et al. 2006b who assume $L_{\text{H}_2\text{O}} \propto R_{\text{cr}}^2$). We then expect $L_{\text{H}_2\text{O}} \propto L_{\text{AGN}}^{0.38} M_{\text{BH}}^{0.62}$. If we further assume that AGNs radiate with a roughly fixed Eddington ratio η as a function of black hole mass, so that $L_{\text{AGN}} = \eta L_{\text{Edd}} \propto M_{\text{BH}}$, we eventually reach $L_{\text{H}_2\text{O}} \propto L_{\text{AGN}} \propto M_{\text{BH}}$.

It is well-known that there exists a tight correlation between the central black hole mass (M_{BH}) and the velocity dispersion of the black hole host (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Gültekin et al. 2009): $M_{\text{BH}} \propto \sigma^4$. The optical luminosity also correlates with the black hole mass but with a larger scatter (Magorrian et al. 1998; Gültekin et al. 2009): $M_{\text{BH}} \propto L(\text{Optical})$. For AGN strength, the $[\text{O III}]\lambda 5007$ luminosity is a reasonably reliable indicator (e.g., Heckman et al. 2005). In Figure 10, assuming $L_{\text{H}_2\text{O}} \propto M_{\text{BH}} \propto L_B \propto \sigma^4$ and $L_{\text{H}_2\text{O}} \propto L_{\text{AGN}} \propto L_{[\text{OIII}]\lambda 5007}$, we fit the intercepts (at 0) and obtain -39.6 ± 0.2 , -38.6 ± 0.2 , -7.0 ± 0.1 , and -6.5 ± 0.1 , for $\log_{10} L_{[\text{OIII}]\lambda 5007, \text{cor}}$, $\log_{10} L_{[\text{OIII}]\lambda 5007, \text{obs}}$, $\log_{10} \sigma$, and M_B , respectively. We show these fits with dotted lines. If one takes our best-fit correlations in Section 3.1 at face value, it implies a weaker dependence of maser luminosity on black hole mass and AGN activity than the simplified theory.

The analysis above is simplified. For example, the Eddington ratio η is not necessarily independent of black hole mass for masers, even if it is so for AGNs. If masers are powered by AGN luminosity, then a high enough Ed-

dington ratio is required to pump up a strong maser. This hypothesis can explain what we found in Section 2.2.2, that [O III] $\lambda 5007$ luminosity is more important a factor than M_B and σ when determining detection efficiency. It is also interesting that the slopes above are all steeper than the best-fit ones. As we discussed in Section 3.1, the best-fit slopes could be flatter than real ones due to the detection bias. Considering the large uncertainties caused by the variability and the assumption of isotropy in maser luminosity and the small sample size, we conclude that our fitting results are in reasonable agreement with the simplified theory and that maser strength is indeed correlated with the central black hole mass and the AGN activity of the host galaxies.

Previous studies have also found correlations between the isotropic luminosity and various properties of the host galaxies. Kondratko et al. (2006b) find that $L_{\text{H}_2\text{O}} \propto L_{2-10}^2$, where L_{2-10} is the 2–10 keV X-ray luminosity of the host galaxy. Zhang et al. (2010, see also Henkel et al. 2005; Castangia et al. 2008; Surcis et al. 2009) find there appears to be a correlation between L_{FIR} and $L_{\text{H}_2\text{O}}$, where L_{FIR} is the total far-infrared (FIR) luminosity of the host galaxy. However, they do not claim to find a significant correlation between extinction-corrected $L_{[\text{O III}]\lambda 5007, \text{cor}}$ and $L_{\text{H}_2\text{O}}$, likely due to the smaller sample size in their study.

3.3. Masers favor high-extinction systems: a geometrical effect?

In Figure 4, we showed that maser detection rate is higher at higher $\text{H}\alpha/\text{H}\beta$, thus higher extinction. Greenhill et al. (2008) and Zhang et al. (2010) also find that there is a high incidence of Compton-thick systems among AGN masers. If masers are only located on the nuclear disk surrounding the central black hole, then this preference of higher-extinction systems could be explained as a geometrical effect.

The specific intensity of maser emission scales with the cube of the pumping gain length (l) along the path (e.g., Strelitskii 1984; Lo 2005): $L_{\text{H}_2\text{O}} \propto l^3$. If masers originate in gas clouds in the circumnuclear disk, we can only observe masers when the disk is inclined so that the gain length along the line-of-sight is long enough. According to the proposed unified AGN models (e.g., Antonucci & Miller 1985), when the circumnuclear disk is inclined, the optical extinction due to the dusty torus and the X-ray obscuring column (N_H) are correspondingly higher. Naturally, masers are more often found to be in high-extinction systems. Under this theory, we expect total isotropic maser luminosity on average to be higher in higher-extinction systems, since the average gain length should be longer. However, we did not find a convincing linear relation between $\log_{10} L_{\text{H}_2\text{O}}$ and $\text{H}\alpha/\text{H}\beta$ in Figure 11. This could be because $\text{H}\alpha/\text{H}\beta$ is not a direct proxy of gain length, or the intrinsic scatter of the relation is too big to detect in the small sample we currently have. Meanwhile, some masers, e.g., NGC 1052 (Claussen et al. 1998) and NGC 262 (Mrk 348, Peck et al. 2003), are likely to be associated with jets but not disks. These systems could have greatly increased the scatter of the relation. It is also possible that the inclination of the host galaxy can affect the observed Balmer decrement, and thus increase the scatter.

On the other hand, if this theory is correct, then many extragalactic nuclear masers should be disk systems, but more than half of current maser detections lack evidence of association with disks (or jets). To confirm this theory requires further investigations with larger samples and follow-up VLBI observations of maser detections.

4. SUGGESTIONS ON SURVEY STRATEGIES

Our results suggest that if we can improve the observational sensitivity, we should be able to detect more nuclear masers. Given the current sensitivity, however, we can still improve the detection efficiency. Since there exist large optical spectroscopic surveys, such as SDSS, 2dFGRS, and 6dFGS, we suggest that maser surveys primarily interested in efficiency should select AGN targets from these surveys and rank them by extinction-corrected [O III] $\lambda 5007$ flux. As an example, we illustrate this strategy in Figure 12.

In Figure 12, we plot $\log_{10} L_{[\text{O III}]\lambda 5007}$ against redshift for all the 33 detections and 1030 non-detections with SDSS spectroscopy. Note in Figure 9, we showed that 0.1 Jy km s^{-1} represents the effective flux limit in maser surveys. To relate this limit to $L_{[\text{O III}]\lambda 5007}$, we use the dotted lines in Figure 10: $\log_{10} L_{\text{H}_2\text{O}} = -39.6 + \log_{10} L_{[\text{O III}]\lambda 5007, \text{cor}}$ and $\log_{10} L_{\text{H}_2\text{O}} = -38.6 + \log_{10} L_{[\text{O III}]\lambda 5007, \text{obs}}$, where $L_{\text{H}_2\text{O}}$ is in L_\odot and $L_{[\text{O III}]\lambda 5007}$ is in erg s^{-1} . This conversion translates the limit 0.1 Jy km s^{-1} in maser flux into $7.6 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ in extinction-corrected [O III] $\lambda 5007$ flux, and $7.6 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ in observed [O III] $\lambda 5007$ flux. These limits are the solid lines in Figure 10. To take into account the scatter in the $L_{\text{H}_2\text{O}}-L_{[\text{O III}]\lambda 5007}$ relation, we shift the limits downward by -1.0 dex to $7.6 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ and $7.6 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ and show them with the dashed lines. Among the 33 detections, 30 (32) have $L_{[\text{O III}]\lambda 5007, \text{cor}}$ ($L_{[\text{O III}]\lambda 5007, \text{obs}}$) brighter than the dashed line. For $L_{[\text{O III}]\lambda 5007, \text{cor}}$ ($L_{[\text{O III}]\lambda 5007, \text{obs}}$), the detection rates above and below the dashed line are $6.9\% \pm 1.2\%$ ($4.3\% \pm 0.8\%$) and $0.5\% \pm 0.3\%$ ($0.3\% \pm 0.3\%$); the detection rates above and below the solid line are $16.0\% \pm 4.1\%$ ($9.2\% \pm 2.2\%$) and $2.0 \pm 0.5\%$ ($1.9\% \pm 0.5\%$).

Therefore, if we rank AGN targets by extinction-corrected [O III] $\lambda 5007$ flux, we can significantly improve the detection efficiency, from an overall $\sim 3\%$ to $\sim 16\%$ for the strongest [O III] $\lambda 5007$ emitters. Furthermore, given the current sensitivity, observing AGNs with extinction corrected [O III] $\lambda 5007$ flux lower than the dashed line yields a very low detection rate of $\lesssim 1\%$. The contrast among these detection rates suggests that ranking source lists according to extinction-corrected [O III] $\lambda 5007$ is effective in maximizing detection efficiency. If extinction correction (i.e., $\text{H}\alpha/\text{H}\beta$) is not available, we suggest that maser surveys rank AGN targets with the observed [O III] $\lambda 5007$ flux. If the observed [O III] $\lambda 5007$ flux is not available either, we suggest that maser surveys rank AGN targets by velocity dispersion, or by optical luminosity. This strategy should give a higher detection efficiency than a blind survey.

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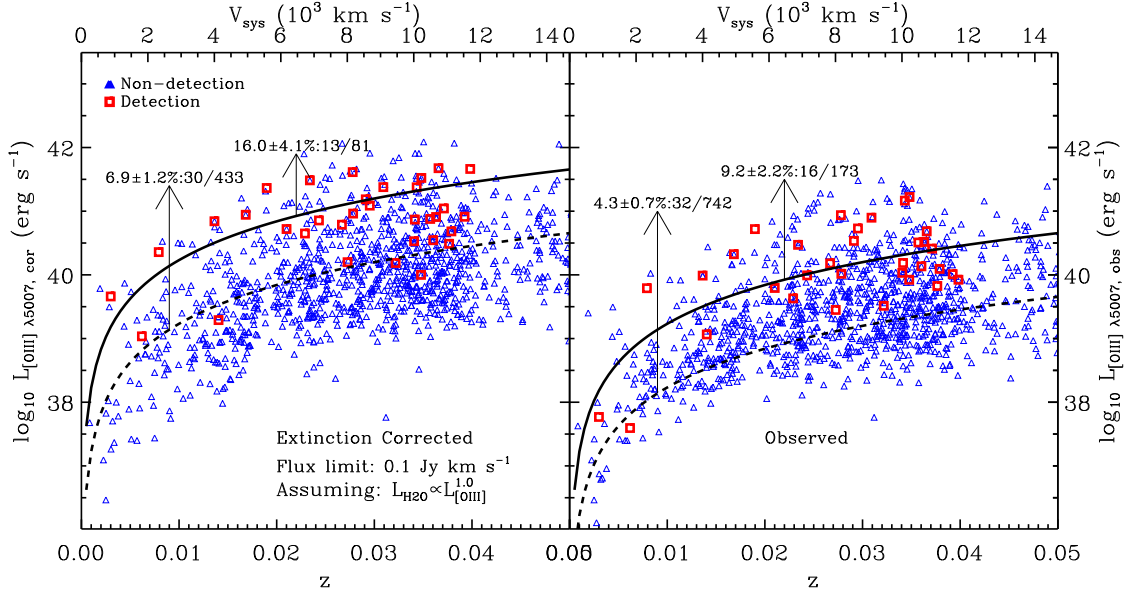


FIG. 12.— [O III] $\lambda 5007$ luminosity as a function of redshift. We plot all detections and non-detections in the SDSS spectroscopic sample. The solid lines show the assumption of maser flux limit 0.1 Jy km s^{-1} and $L_{\text{H}_2\text{O}} \propto L_{[\text{O III}]\lambda 5007}$ (the dotted lines in Figure 10). The dashed lines are the flux limit shifted downward by -1.0 dex, to take into account the scatter in the $L_{\text{H}_2\text{O}} - L_{[\text{O III}]\lambda 5007}$ relation. The percentages at the end of arrows show the detection rates above the corresponding lines and the two numbers show the number of detections and galaxies surveyed for maser emission (detections plus non-detections).

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TABLE 1
PHYSICAL PARAMETERS OF EXTRAGALACTIC WATER MASER SOURCES

Source	V_{sys}^1	$L_{\text{H}_2\text{O}}^2$	Ref($L_{\text{H}_2\text{O}}$) ³	$F_{[\text{OIII}]}^4$	H_α/H_β^5	Ref($F_{[\text{OIII}]}$) ⁶	σ^7	Ref(σ) ⁸	M_B^9	Ref(M_B) ¹⁰
NGC 23 (Mrk 545)	4566	2.3	BG08	1200	5.2	DD88	...	...	-21.50	DeV91
NGC 17 (Mrk 938) [†]	5881	...	...	...	...	...	...	...	...	...
2MASX J00114518-0054303	14384	...	...	...	...	...	...	...	-19.58	SDSS
NGC 235A	6664	2.0	Kondratko06	...	...	...	198	Wegner03	-21.02	DeV91
NGC 262 (Mrk 348)	4507	2.6	Henkel05	22710	6.02	Bassani99	185	McElroy95	-20.54	DeV91
NGC 291	5705	...	...	6431	4.97	SDSS	109	SDSS	-20.14	SDSS
ESO 013-G012	5047	...	...	...	...	...	...	...	...	...
NGC 449 (Mrk 1) [†]	4780	1.7	Henkel05	60000	...	Whittle92	115	NW95	-19.53	DeV91
NGC 520	2281	0.1	Castangia08	412.4	4.13	Ho97	41	Ho09	-20.55	DeV91
2MASX J01260163-0417564	5639	...	...	...	...	...	...	...	...	...
NGC 591 (Mrk 1157) [†]	4547	1.4	Henkel05	23000	...	Whittle92	95	NW95	-20.50	DeV91
NGC 613	1481	1.2	Kondratko06	...	...	...	125	McElroy95	-21.08	DeV91
		1.2	Castangia08	...	...	...	...	...	...	...
IC 0184	5382	1.4	Kondratko06	...	...	...	...	...	-20.00	DeV91
2MASX J02140591-0016371	11205	...	...	...	...	...	...	...	-18.59	SDSS
Mrk 1029	9076	...	...	...	...	...	...	...	...	...
NGC 1052	1510	2.1	Henkel05	33068	2.35 ^b	Ho97	187	Wegner03	-19.85	SDSS
NGC 1068 (M 77) [†]	1137	2.2	Henkel05	3497963	5.29	Ho97	162	Ho09	-21.68	DeV91
		1.7	KGM06	...	...	...	...	...	...	...
NGC 1106	4337	0.9	BG08	...	...	...	146	Wegner03	-21.17	DeV91
2MASX J02532956-0014052	8622	...	...	1757	5.0	SDSS	96	SDSS	-18.18	SDSS
Mrk 1066	3605	1.5	Henkel05	24000	8.51	Whittle92	105	NW95	-20.60	DeV91
NGC 1194 [†]	4076	...	...	2340	5.85	SDSS	144	SDSS	-20.06	SDSS
NGC 1320 (Mrk 607) [†]	2663	...	...	...	...	...	...	...	...	...
2MASX J03364614-0750236	11719	...	...	...	...	...	...	...	...	...
NGC 1386 [†]	868	2.1	Henkel05	99244	5.7	Bassani99	187	McElroy95	-18.52	DeV91
2MASX J03381036+0114178	11926	...	...	...	...	...	...	...	...	...
(IRAS03355+0104)		...	...	...	...	...	...	...	...	...
4C +05.19	790000	...	...	...	...	...	...	...	...	...
(2MASX J04143774+0534423)		...	...	...	...	...	...	...	...	...
2MASX J04405494-0822221	4527	...	...	...	...	...	...	...	...	...
(IRAS F04385-0828)		...	...	...	...	...	...	...	...	...
UGC 3193 [†]	4454	2.4	BG08	...	...	...	...	...	-19.93	DeV91
NGC 1741 (Mrk 1089)	4039	...	...	...	...	...	...	...	...	...
CGCG 468-002	5454	...	...	...	...	...	...	...	...	...
UGC 3255	5669	1.2	Henkel05	...	...	...	...	...	-19.98	DeV91
UGCA 116	789	...	...	...	...	...	...	...	...	...
Mrk 3	4050	1.0	Henkel05	439100	6.67	Bassani99	248	McElroy95	-20.70	DeV91
VII Zw 073	12391	2.2	Kondratko06	...	...	...	...	...	...	...
NGC 2273 (Mrk 620)	1840	0.8	Zhang06	27618	5.08	Ho97	149	Ho09	-19.95	DeV91
UGC 3789 [†]	3325	2.6	BG08	...	...	...	...	...	-20.47	DeV91
NGC 2410	4681	...	...	3306	4.88	SDSS	166	SDSS	-20.86	SDSS
Mrk 78	11137	1.5	Henkel05	66000	6.46	Polletta96	114	McElroy95	...	...
IC 0485 [†]	8338	...	...	585.8	6.29	SDSS	187	SDSS	-20.24	SDSS
Mrk 1210 (UGC 04203, Phoenix)	4046	1.9	Henkel05	95660	5.2	Bassani99	114	Gu06	-19.71	DeV91
SDSS J0804+3607	198000	...	...	...	...	...	...	...	...	...
2MASX J08362280+3327383 [†]	14810	...	...	...	...	...	...	...	-20.24	SDSS
NGC 2639 [†]	3336	1.4	Henkel05	1858	4.06	Ho97	179	Ho09	-20.95	SDSS
NGC 2781	2053	...	...	...	...	...	...	...	...	...
2MASX J09124641+2304273	10861	...	...	1078	4.07	SDSS	74	SDSS	-19.12	SDSS
NGC 2782	2543	1.1	Henkel05	5944	6.5	Ho97	183	Ho09	-20.41	SDSS
NGC 2824 (Mrk 394)	2760	2.7	Henkel05	...	...	...	122	McElroy95	-19.09	SDSS
SBS 0927+493	10167	...	...	570.9	5.11	SDSS	147	SDSS	-20.70	SDSS
UGC 5101	11802	3.2	Zhang06	226.9	11.7	SDSS	189	SDSS	-21.28	SDSS
NGC 2960 (Mrk 1419) [†]	4932	2.6	Henkel05	4400	...	DD88	...	...	-20.84	SDSS
NGC 2979 [†]	2720	2.1	Henkel05	...	...	...	112	Gu06	...	...
NGC 2989	4146	1.6	BG08	...	...	...	...	...	-20.66	DeV91
NGC 3081	2391	...	...	...	...	...	...	...	...	...
NGC 3079 [†]	1116	2.7	Henkel05	176.2	28.4	Ho97	182	Ho09	-19.62	DeV91
		2.5	Kondratko05	...	...	...	...	...	...	...
2MASX J10115058-1926436	8065	...	...	...	...	...	...	...	...	...
NGC 3160	6920	...	...	358.5	6.66	SDSS	155	SDSS	-20.32	SDSS
IC 2560 [†]	2925	2.0	Henkel05	...	...	...	144	Gu06	-21.09	DeV91
NGC 3256	2804	0.8	Surcis09	...	...	...	127	Oliva95	-21.49	DeV91
UGC 5713 [†]	6312	...	...	622.0	6.2	SDSS	168	SDSS	-20.24	SDSS
Mrk 34 [†]	15140	3.0	Henkel05	67000	10.5	Polletta96	...	...	...	...
NGC 3393 [†]	3750	2.4	Kondratko06	124344	4.12	Bassani99	184	McElroy95	-20.99	DeV91
		2.6	Zhang06	...	...	...	...	...	...	...
UGC 6093 [†]	10828	...	...	452.0	4.14	SDSS	160	SDSS	-21.53	SDSS
2MASX J11093314+2837393	11422	...	...	371.7	4.76	SDSS	149	SDSS	-20.41	SDSS
NGC 3620	1680	0.5	Surcis09	...	...	...	...	...	...	...
CGCG 185-028	10455	...	...	298.7	3.19	SDSS	204	SDSS	-21.14	SDSS

TABLE 1
PHYSICAL PARAMETERS OF EXTRAGALACTIC WATER MASER SOURCES

¹ Heliocentric systemic velocity, in km s^{-1} .

² Total maser luminosity assuming isotropic emission of radiation, defined as $L_{\text{H}_2\text{O}} = 0.023 \times \int S(V) dV \times D^2$, where $L_{\text{H}_2\text{O}}$ is in L_\odot , $S(V)$ is the flux (in Jy) at velocity V (in km s^{-1}), and D is luminosity distance (in Mpc). These values were calculated based on $H_0 = 75 \text{ km s}^{-1}$ and We convert values into those with $H_0 = 70 \text{ km s}^{-1}$ in the analysis.

³ References – Henkel05: Henkel et al. (2005); Kondratko05: Kondratko et al. (2005); Kondratko06: Kondratko et al. (2006a); KGM06: Kondratko et al. (2006b); Zhang06: Zhang et al. (2006); BG08: Braatz & Gugliucci (2008); Castangia08: Castangia et al. (2008); Surcis09: Surcis et al. (2009).

⁴ Observed flux of $[\text{O III}] \lambda 5007$, in $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$.

⁵ Ratio of observed flux of $\text{H}\alpha$ to that of $\text{H}\beta$.

⁶ References – DD88: Dahari & De Robertis (1988); Whittle92: Whittle (1992); Polletta96: Polletta et al. (1996); Ho97: Ho et al. (1997); Bassani99: Bassani et al. (1999). In the compilation, we first prefer the homogeneous samples from SDSS and Ho97. We then choose the most recent values for the rest of the sample.

⁷ Velocity Dispersion σ , in km s^{-1} .

⁸ References – McElroy95: McElroy (1995); NW95: Nelson & Whittle (1995); Oliva95: Oliva et al. (1995); Oliva99: Oliva et al. (1999); Wegner03: Wegner et al. (2003); Gerssen04: Gerssen et al. (2004); Gu06: Gu et al. (2006); GH06: Greene & Ho (2006); Ho09: Ho et al. (2009).

⁹ B band absolute magnitude.

¹⁰ References – DeV91: de Vaucouleurs et al. (1991). Magnitudes are corrected for foreground Galactic extinction (Schlegel et al. 1998).

^a The merging system Arp 299 consists of two galaxies, NGC 3690 and IC 694. We assume the maser is associated with NGC 3690.

^b Assumed to be 3 in the analysis.

[†] Likely disk systems.